PREPRINTS
OF THE
STEWARD OBSERVATORY
THE UNIVERSITY OF ARIZONA
TUCSON, ARIZONA

CASE FILE
COPY

A 1:1 APOCHROMAT TRANSFER LENS SYSTEM

W. G. Tifft

R. A. Buchroeder

December 1, 1971

T 71-20

A 1:1 APOCHROMAT TRANSFER LENS SYSTEM

by

W. G. Tifft

R. A. Buchroeder

Steward Observatory
University of Arizona
Tucson, Arizona

December 1, 1971

T 71-20

INTRODUCTION

Work on the IDCADS project (Image Dissector Control and Data System) has been conducted by the Space Astronomy group of Steward Observatory under NASA Contract NSR 03-002-163 and NASA Grant NGR 03-002-153. One of the tasks has been the development of a remote control instrumentation system for use with large telescopes, with emphasis on future application to space telescopes. A prototype system has been constructed for use with the University of Arizona 90-Inch Telescope on Kitt Peak.

The system uses image dissector tubes, a conventional photocell, and photographic plates as detectors for images formed at the Cassegrain focus of the 90-inch telescope. It proved to be impossible to physically locate all of the detector devices directly at the focal plane in the developmental instrument; therefore, it was decided to use an image relay system to transfer selected portions of the image plane to image dissectors and the photographic plate.

This report describes the design of a 1:1 relay system for use with the IDCADS. Design considerations are discussed, alternate designs are outlined, and the "optimum" design is discussed in detail.

The design was a joint effort between the Space Astronomy group and the Optical Design group of the Optical Sciences Center of the University of Arizona. Mr. R. A. Buchroeder of Optical Sciences was responsible for the optical design, Mr. R. H. Tornquist of Space Astronomy was responsible for mechanical design and telescope integration, and Dr. W. G. Tifft, Head of Space Astronomy, was project manager.

I. STATEMENT OF PROBLEM

A. Design Objectives

The image dissector tubes used in IDCADS have an effective cathode diameter of one-inch and the photographic plates have been designed to use a one inch diameter exposure area, so it was decided to use a 1:1 relay system to transfer a 1-inch diameter field.

IDCADS utilizes a guidance system to detect motion of the image due to perturbations of the telescope or to fluctuations in the "seeing" conditions of the atmosphere; guidance signals are sent to electro-mechanical actuators to reposition the relay lens when used in photographic mode so that the motion of the relayed image is reduced as closely as possible to zero. For this reason it was specified that the size and weight of the relay system be kept to a minimum.

It was further specified that the relay lens be relatively maintenance free and to require no adjustments after initial installation and alignment in the IDCADS system.

B. Design Specifications

1. Magnification ratio--1:1.
2. Field size--25.4mm.
3. Relay distance--400mm (focus adjustable by varying the telescope focus).
4. Resolution--0.5 arc sec on the 90-inch telescope (0.05mm or 50μ).
5. Wavelength--usable from 3700A to 1.0 micron.
6. Light transmission--shall be a minimum of 90% over the wavelength range specified in #5.
7. Ghost images and reflections minimized.
8. Transverse motion--transverse motion guidance signals of ±3mm shall not upset the optical correction. These signals may occur at frequencies up to 30Hz, corresponding to approximately 10g.
9. Physical size (of moveable elements)--as small as practical, but in no case to exceed 50mm in diameter by 150mm long.

10. Weight (of moveable elements)--as low as practical, but in no case to exceed 0.5 pounds (227 grams).

II. DESIGN CONSIDERATIONS

A. Aberrations

Any lens system is subject to the five third-order monochromatic aberrations--spherical aberration, coma, astigmatism, Petzval field curvature, and distortion--and to chromatic aberrations. These aberrations are not independent of each other and no lens system can completely eliminate all of them simultaneously; also, due to the existance of higher-order aberrations, the third-order terms are rarely set to zero but are selected to give uniform correction over the field of view.

1. Spherical aberration--a uniform flare generally found in simple spherical lenses due to a failure to focus all rays at a single point. While it is the distinctive aberration on the optical axis, it superimposes over the entire field of view. This aberration may be reduced or eliminated by aspheric polishing (deviation from a true spherical surface), a very tedious and expensive process, or by using compound lenses made from two or more simple lens fabricated from different types of optical glass. For this application, compound lenses are clearly indicated.
2. Coma--an off-axis defect most often found in simple lenses caused by the failure of rays which deviate by a small angle from the central axis to focus at a point, but instead to form a comet-like distorted image. However, a 1:1 symmetrical relay with a field lens can be perfectly freed from this defect.
3. Astigmatism--a defect not corrected by symmetry, this aberration increases rapidly with increasing field of views. It manifests

itself as a pair of focal lines, one inside of the "best focus" and one outside. The best focus is a circular blur which increases as the square of the distance from the optical axis. Astigmatism is negligible for this system because the angle of the field is small.

4. Petzval Curvature--an optical system which has all of the other aberrations corrected to zero will have an image which falls on a curved focal surface known as the "Petzval surface". This aberration arises solely from the power of the optical elements and generally can only be eliminated with complex lens forms.
5. Distortion--non-uniform magnification over the field, usually increasing with the cube of the distance from the optical axis. In a symmetrical 1:1 relay with a field lens, it is possible to eliminate this defect.
6. Chromatic Aberration--the index of refraction of any optical material varies with wavelength, so that light of different colors is refracted a different amount. With simple lenses, different colors focus at dfffferent points (axial chromatic aberration) and/or have different magnifications (lateral chromatic aberration).

Lens systems designed for use in the visible region (0.4μ to 0.7μ) are usually achromatic lenses; these lenses have been corrected for spherical aberration in one color of the spectrum and for axial chromatic aberration for two colors. However, such a lens has the chromatic aberration reduced to zero only at the two wavelengths selected for correction; at other wavelengths, appreciable chromatic aberration (called secondary spectrum) may remain. For the system under design the spectrum is so broad (0.37μ to 1.0μ) that it was apparent that secondary spectrum would cause serious design problems. It was felt that an apochromatic lens would have to be used; such a lens has been designed to correct for spherical aberration in two colors and the axial chromatic aberration in three colors.

Apochromatic lenses may have a material such as flourite (calcium flouride) for one or more of the elements. Because flourite has a low refractive index, low dispersion, and a partial dispersion ratio different from glass, a better simultaneous correction for primary and secondary chromatic aberration and spherical aberration can be accomplished by its use as a positive element in a lens system. For example, if a flourite positive element is used with a flint glass negative element, a steep interface between the elements is attained when the chromatic aberration is corrected. The over correction for spherical aberration, resulting from the steep interface and the large refractive difference at it, can be used to compensate for the under correction of other elements. By virture of flourite's partial dispersion ratio being markedly different from that of glass, secondary chromatic aberration is favorably reduced.

B. Size and Weight

A preliminary investigation revealed that the limitation on lens diameter would require the use of a field lens in conjunction with a relay system. Actually, this would probably be the preferred optical configuration even without the size limitation since the use of a field lens results in a system which is relatively insensitive to misalignment.

C. Maintainability

Since the lens will be used in an application where it is not convenient to check alignment and focus at frequent intervals, it is important that the lens be rugged and insensitive to misalignment. Particles of dust or lint on any of the lens surfaces should not be reimaged at the focal plane.

Flourite is a brittle, soft material which is easily scratched and is prone to fracture under thermal and mechanical shock. It is, therefore, desirable that any flourite elements be so located that their surfaces are not exposed to accidental contact or to cleaning and dusting by well-meaning, but inexperienced, hands.

III. DESIGN

A. Field Lens

The field lens design is related to that of the rest of the system, since it is not at the f/9 90-inch telescope focus exactly. If it were placed at this focus, it would in theory have no effect except to pass the principal ray through the relay and its shape would be immaterial. However, if so placed, it would almost certainly introduce a sharply focussed ghost image, as well as having any beauty defects or surface dust reimaged at the new focal plane.

The final design of the field lens is shown in Figure 1. It is a plano-convex lens made of UBK-7 glass, 30mm in diameter, 6.0mm thick, and with a radius of curvature of 100.0mm.

B. Relay System

As was mentioned in Section II, it was felt that an apochromatic lens would be required. However, in order to test this hypothesis, a design was made of a normal achromat, using good common glasses, with chromatic correction made at the F(blue hydrogen line, 0.4861μm) and the C(red hydrogen line, 0.6563μm) points of the spectrum. Figure 2 shows the real focus curve for this achromat; note that the defocusing at the extremes of the desired spectrum is intolerable. It was, therefore, confirmed that an apochromat would be required.

FIGURE 1

FIELD LENS -

1. Dimensions are in mm.
2. Surfaces marked "P" are polished, all others ground.
3. Chamfer all edges .5 x 45°.
4. Centered to .05 edge run out.
5. Coating to be UV HEA registered or equivalent.
6. Material: UBK-7 glass (Schott #517643).
7. Specification per drawing #01085 to apply.

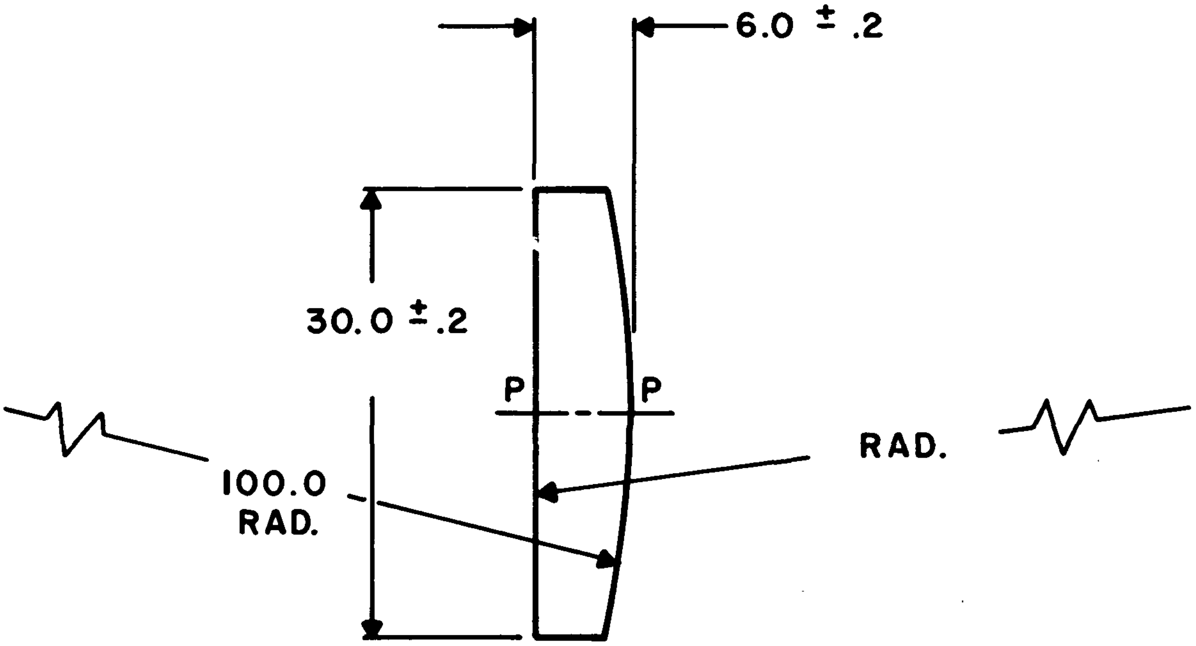


FIGURE 1

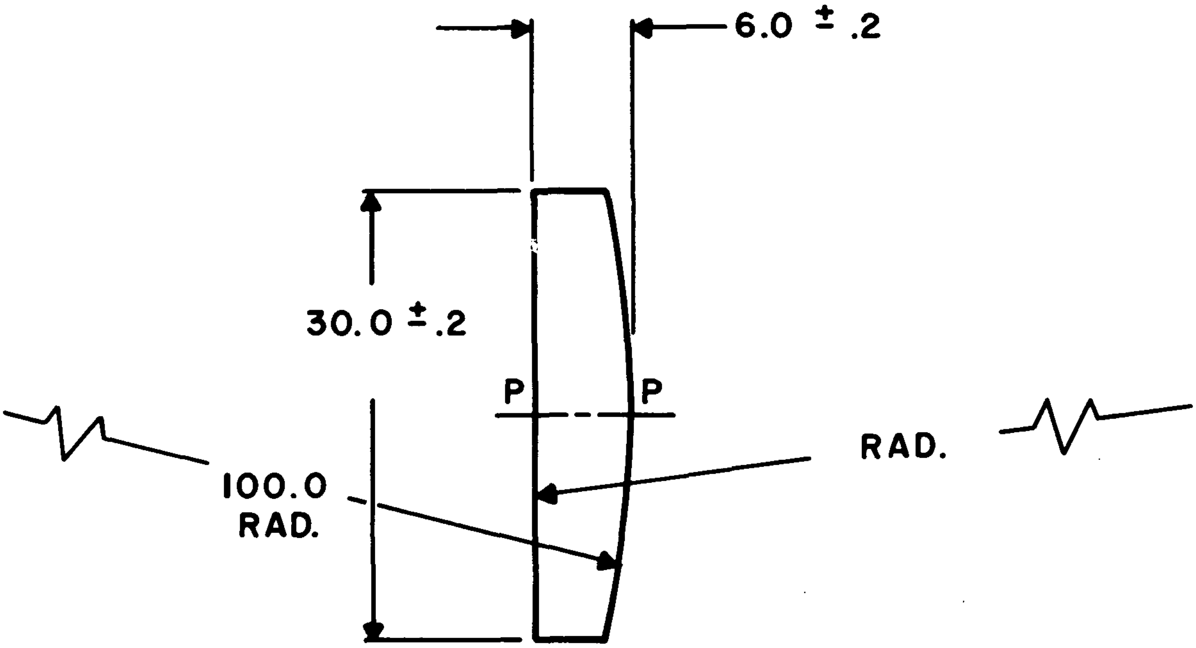


FIGURE 1

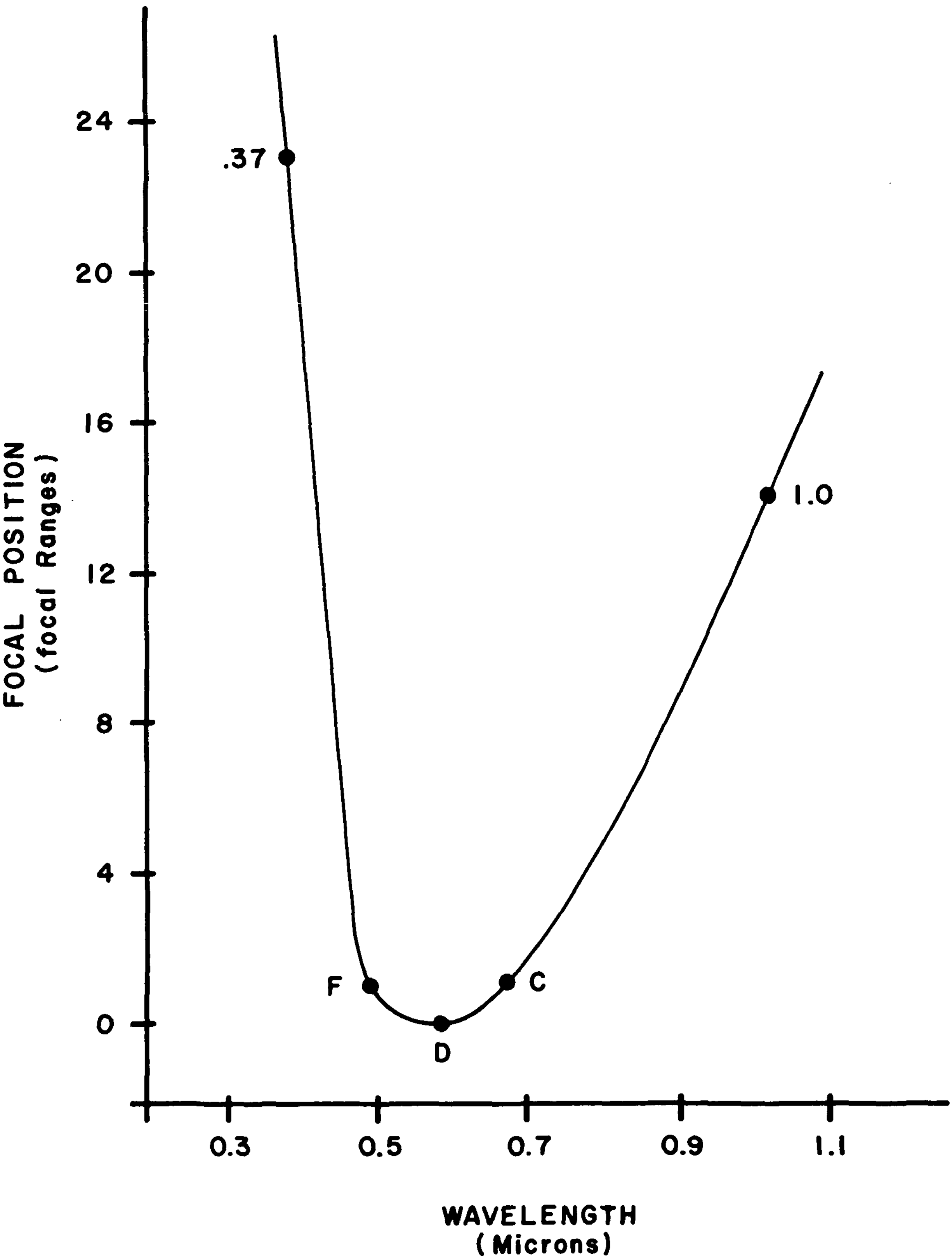

24
20
16
12
8
4
0
FOCAL POSITION
(focal Ranges)
.37
1.0
F
C
D
0.3
0.5
0.7
0.9
1.1
WAVELENGTH
(Microns)

FIGURE 2

It is theoretically possible to design an apochromat using ordinary optical glasses; however, such a design would probably require seven or eight different elements and would be very expensive to manufacture and difficult to assemble and align. It was, therefore, decided to investigate the use of a flourite apochromat. Figure 3 shows the improvement possible with a flourite apochromat. In terms of the resolution requirements, the flourite lens would allow one to focus on a bright image, then photograph in any selected wavelength without refocusing.

Figures 2 and 3 are for air spaced triplets similar to the configuration of Figure 4. However, a triplet is sensitive to manufacturing errors and would have two flourite elements as the outside elements, subject to damage. A pair of cemented doublets, as shown in Figure 5, was finally selected as the "optimum" solution to the problem. Each doublet is identical, resulting in savings during fabrication and greater dependability of assembly. By their nature, since the bulk of correction is carried at the cemented interface, doublets are less sensitive to misalignment during assembly. Should the lenses ever become loose in their cells, or the cells slightly bent, the optical correction would not be greatly affected. An air spaced triplet, on the other hand, is susceptable to failure under abusive conditions.

An additional advantage of using cemented doublets is that surface reflections are minimized. This is especially useful when using flourite, since it tends to scatter no matter how carefully polished. Ghosts are unlikely to arise in the cemented doublet relay system since all air-glass surfaces are convex. Also, the flourite lenses are the internal elements, protected from damage. Figure 6 shows the final configuration of the twin doublets.

The final design was aided by a computer program, ACCOS/GOALS Version

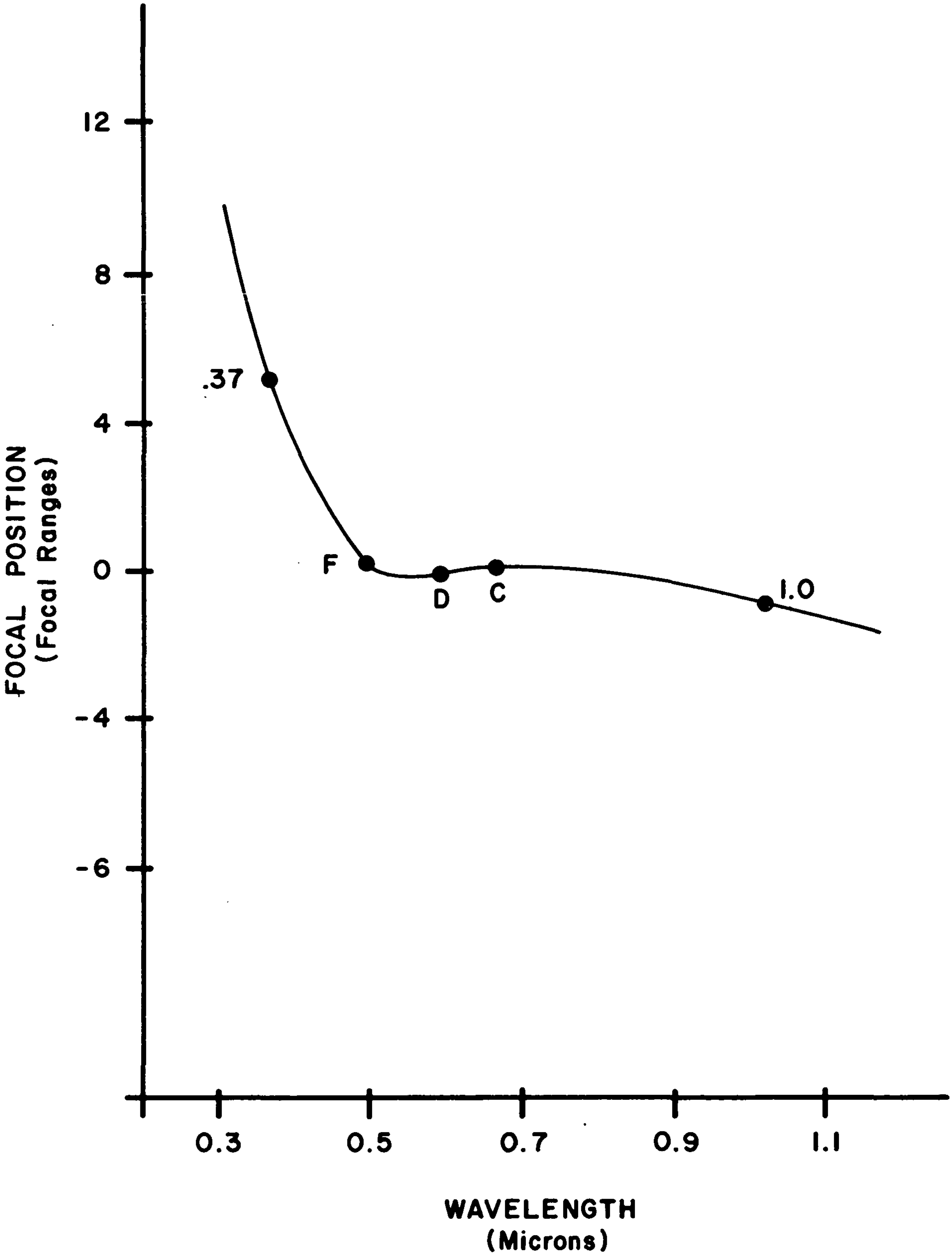

12
8
4
0
-4
-6
FOCAL POSITION
(Focal Ranges)
.37
F
D
C
1.0
0.3
0.5
0.7
0.9
1.1
WAVELENGTH
(Microns)

FIGURE 3

FIGURE 4

AIR SPACED TRIPLET APOCHROMATIC LENS SYSTEM

FIGURE 5

EQUIVALENT APOCHROMATIC LENS SYSTEM,
UTILIZING TWIN AIR SPACED DOUBLETS

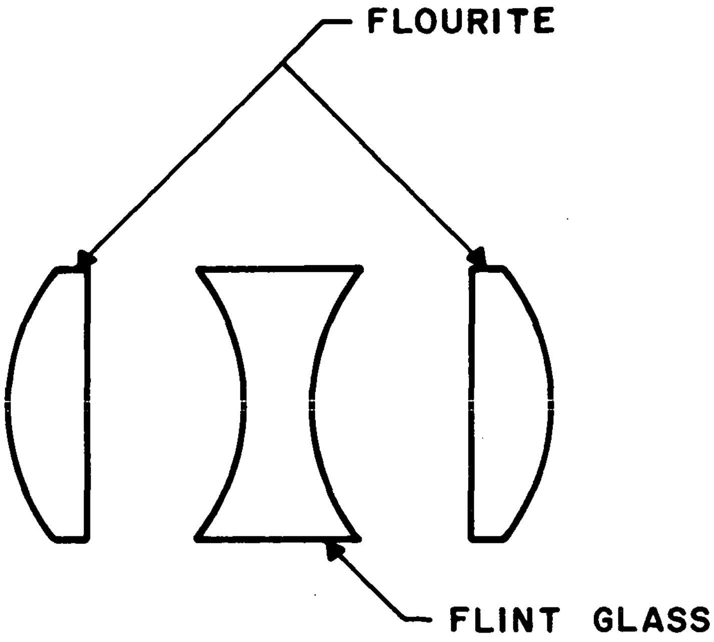


FIGURE 4

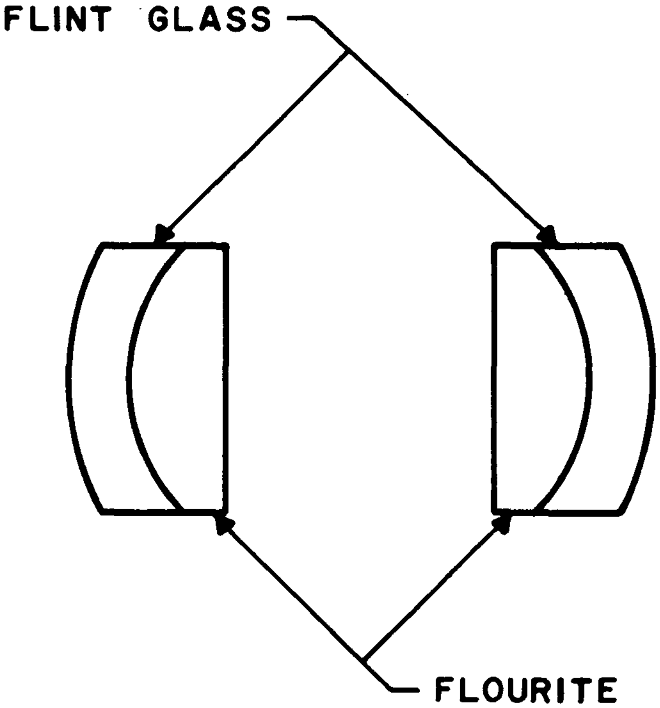
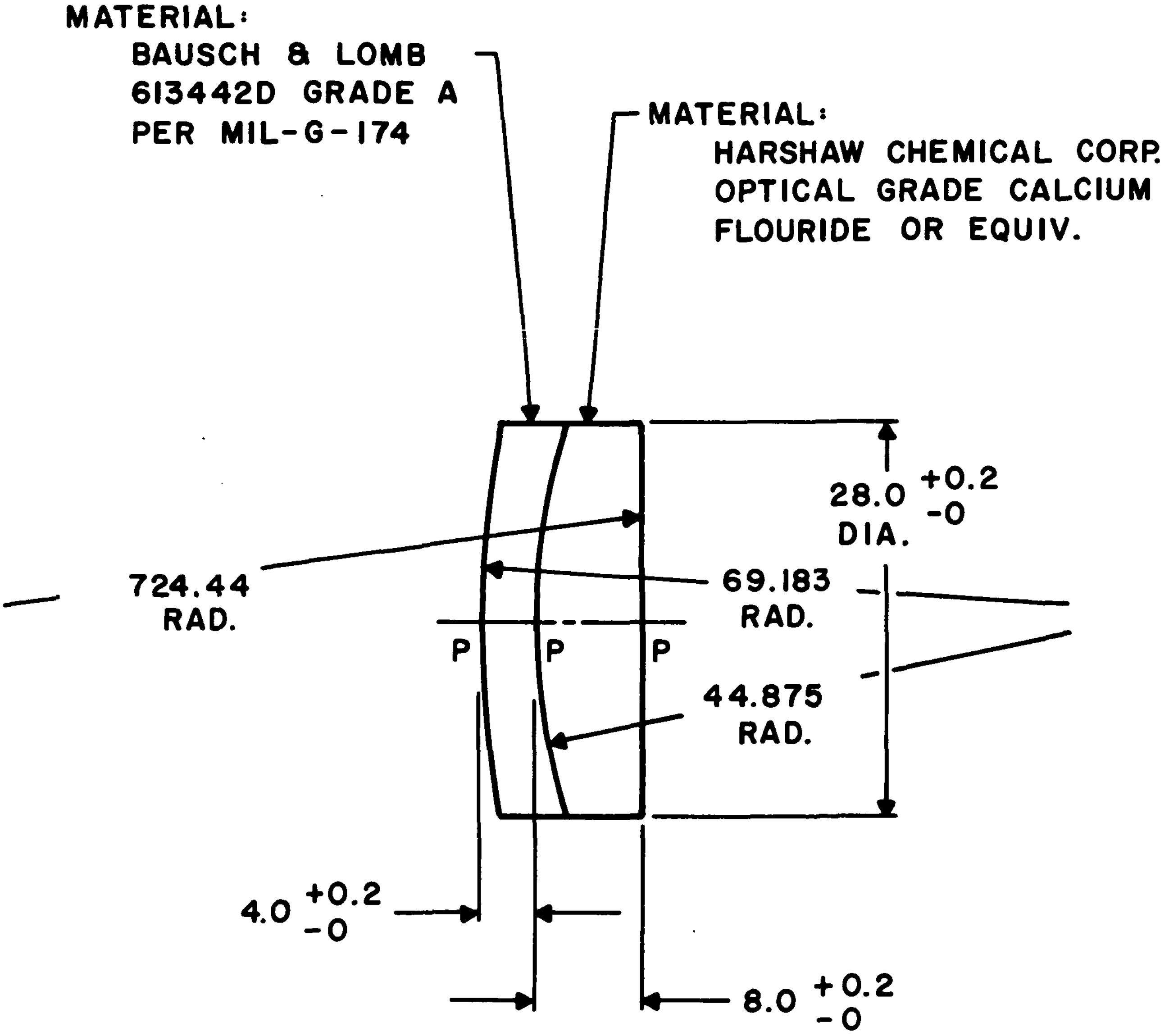


FIGURE 5

FIGURE 6

DOUBLET LENS (One half of Apochromat)

1. Dimensions are in mm.
2. Surfaces marked "P" are polished, all others ground.
3. Chamfer all edges .5 x 45°.
4. Centered to 0.20 edge run out prior to cementing.
5. Specification #01085 shall apply to each lens element.



MATERIAL:
BAUSCH & LOMB
613442D GRADE A
PER MIL-G-174

MATERIAL:
HARSHAW CHEMICAL CORP.
OPTICAL GRADE CALCIUM
FLOURIDE OR EQUIV.

FIGURE 6

IV, originally devised by Scientific Calculations, Inc., of Rochester, New York. Field curvature was found to be the limiting problem. As a design philosophy, spherical aberration was intentionally undercorrected in order to balance the field curvature over the field of view. With this approach, some axial resolution was sacrificed in order to obtain a "flat" field.

Figure 7 shows the focal curve-vs-wavelength (longitudinal chromatic aberration) for the selected design. It shows that the paraxial color is well corrected. Computer calculation of aberration coefficients at five different wavelengths, from 0.4341 to 0.7682μm, shows that correction is well behaved over at least this range; slight refocussing, best determined by experimentation, may be desirable in order to obtain highest resolution at the short and long wavelength extremes.

Figures 8 and 9 show the radial energy distribution (R.E.D.) of the entire system including the 90-inch telescope. The field (maximum) is 25.4mm in diameter. The R.E.D. is perhaps the best means of determining point-resolution, since mean transfer function (MTF) is strictly useful only for continuous objects. Thus, stating that this system will resolve 20 lines/mm is somewhat misleading; 20 lines/mm means bars which have an angular spacing of 0.5 arc-sec in this arrangement. But, resolving an array of black-and-white bars is not the same as resolving points of light separated by 0.5 seconds. This design guarantees the latter.

Figures 10, 11, 12, and 13 are spot diagrams of ray traces performed by the computer for on-axis and three field points, at the "best focus". The circles on these diagrams represent a point 0.1mm in diameter. Note that in focusing the instrument, it is necessary to not focus on axis, but at 0.7 of the 25.4mm diameter field. This gives the best "mean" focus over the entire field. If desired, resolution on axis can be increased

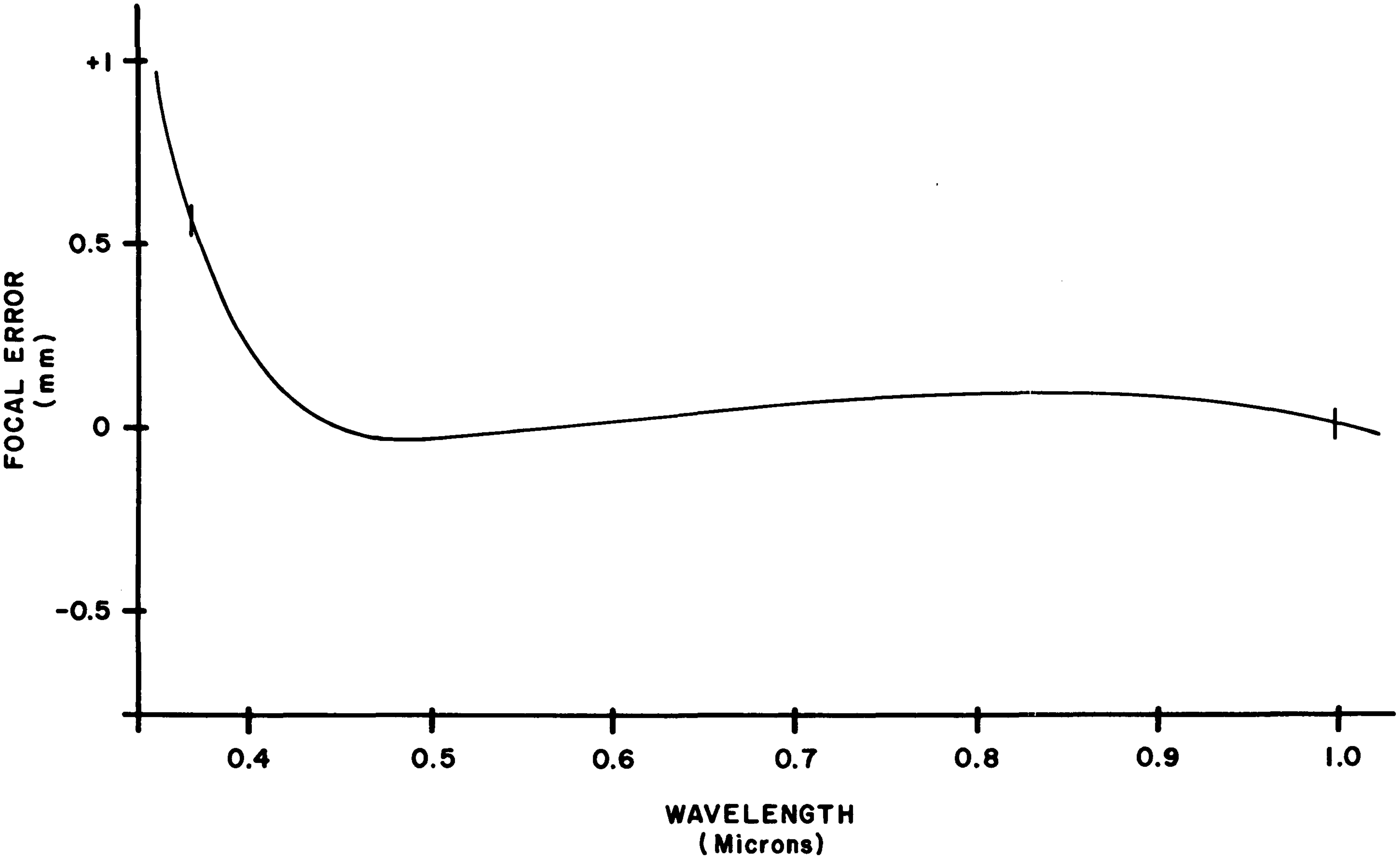
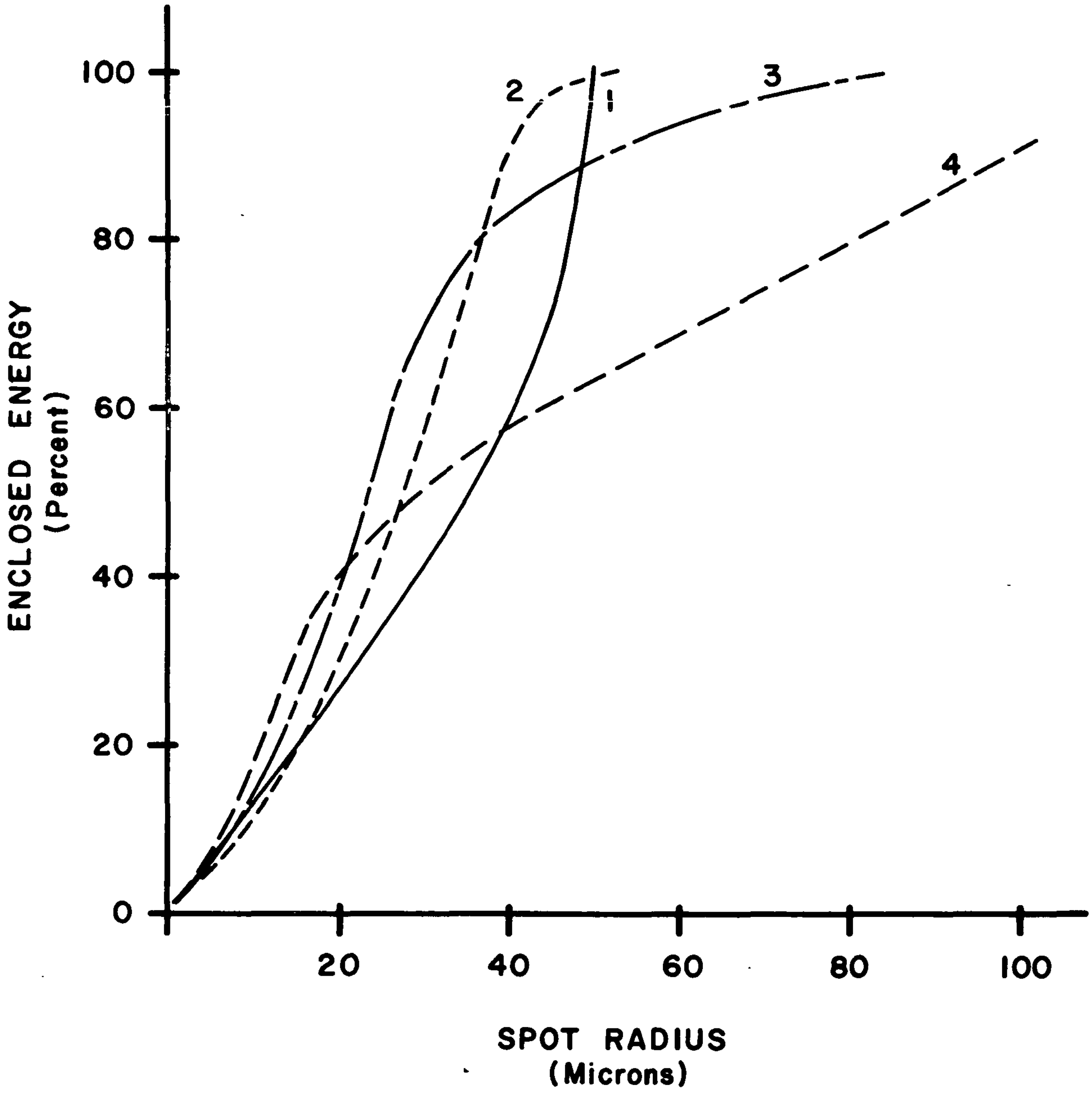


FIGURE 7



100
80
60
40
20
0
ENCLOSED ENERGY
(Percent)
20
40
60
80
100
SPOT RADIUS
(Microns)
1
2
3
4

FIGURE 8

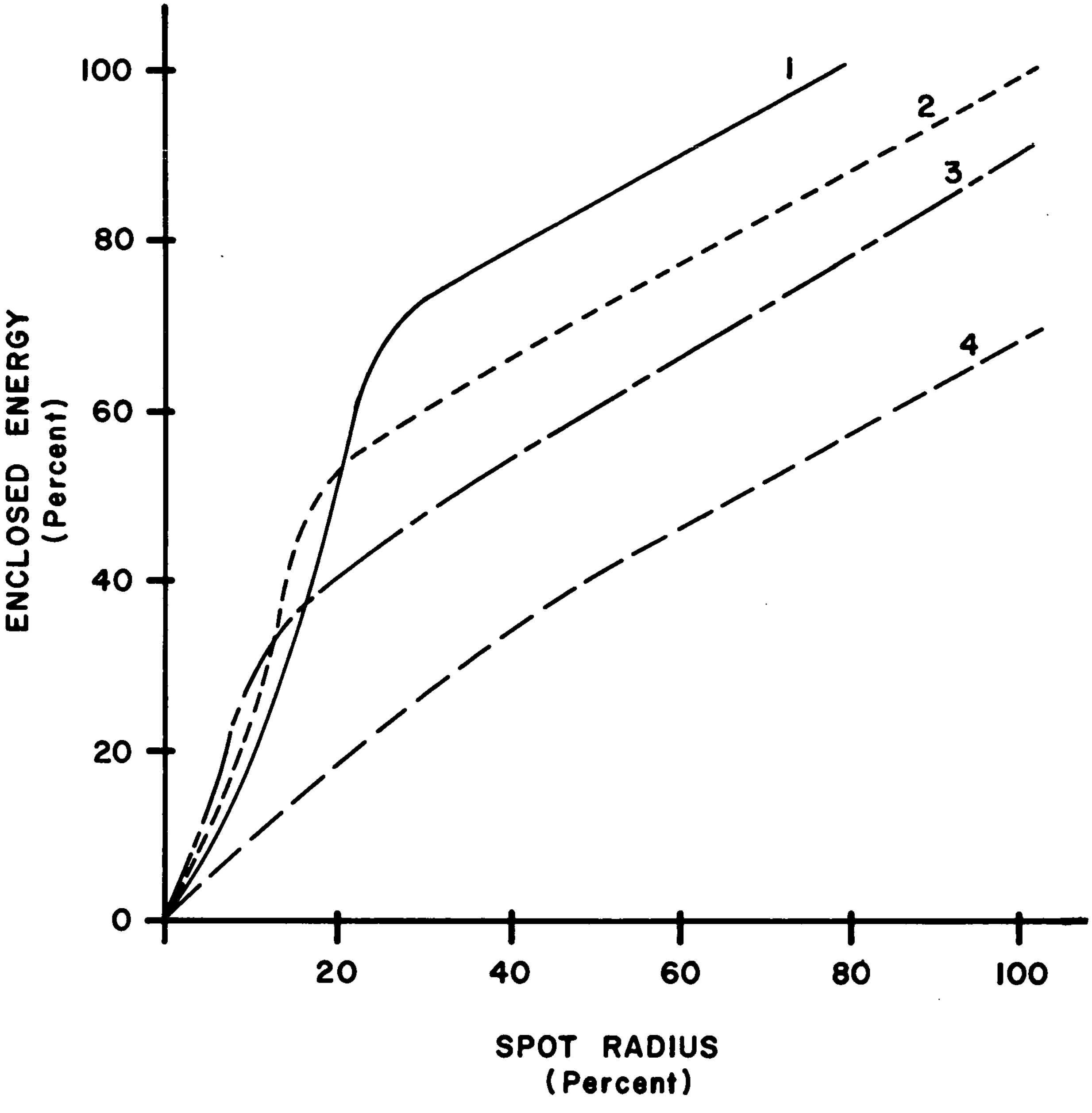
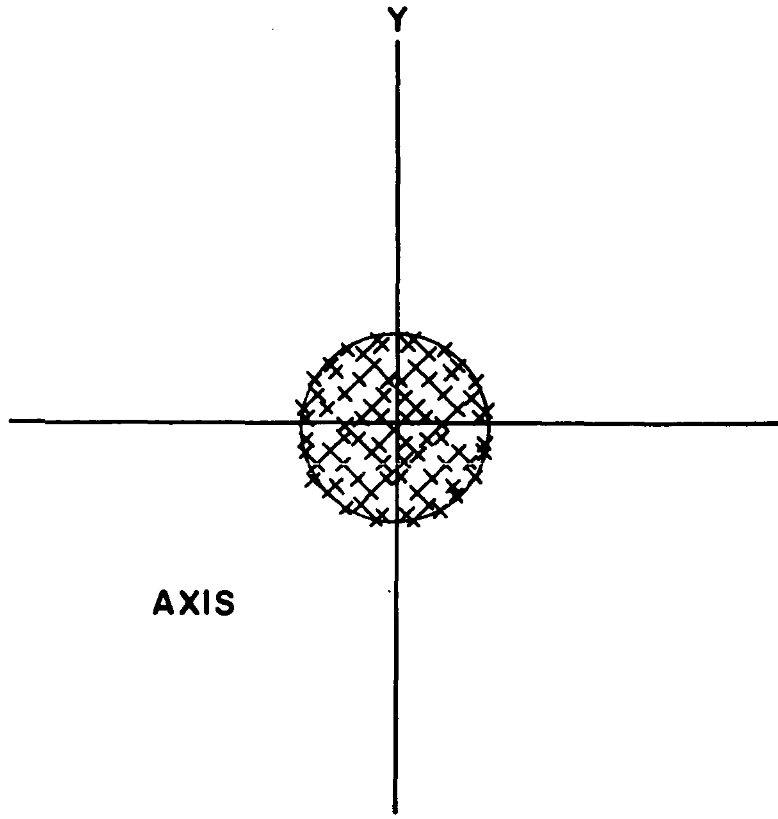
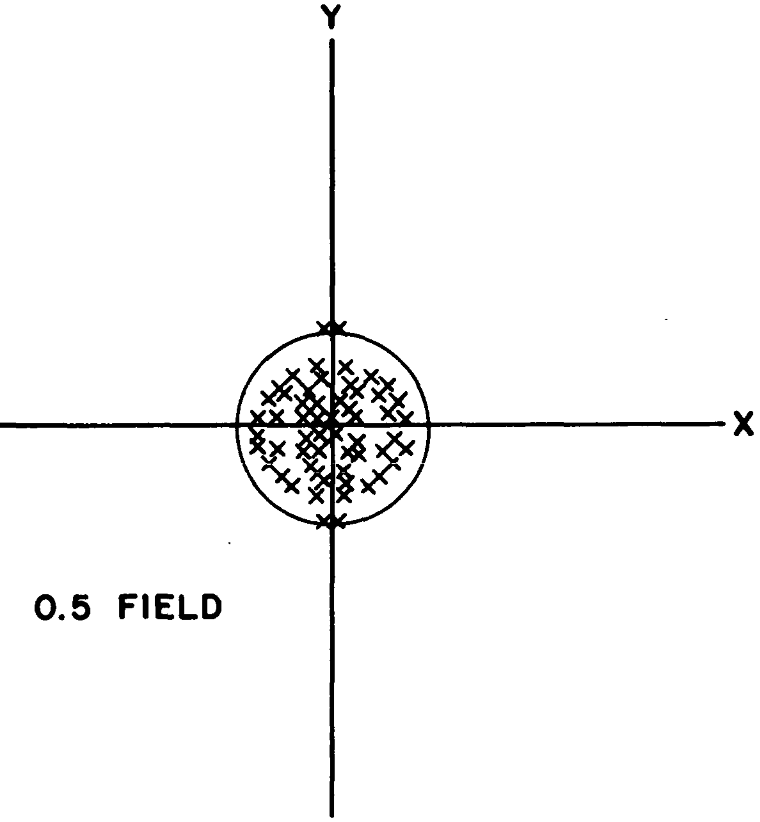

ENCLOSED ENERGY (Percent)
100
80
60
40
20
0
20
40
60
80
100
SPOT RADIUS (Percent)
1
2
3
4

FIGURE 9



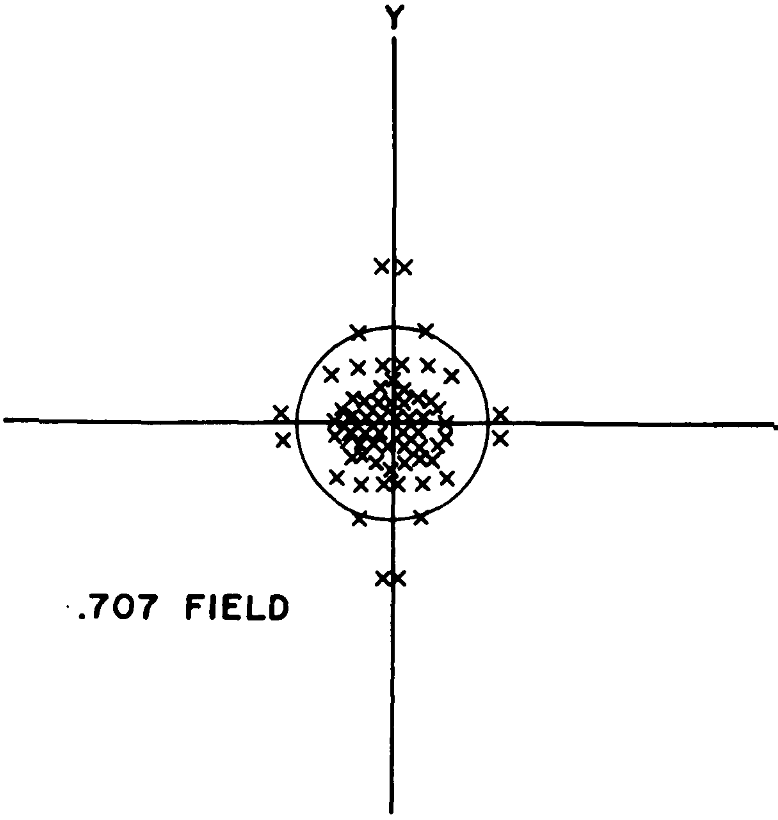
AXIS

FIGURE 10



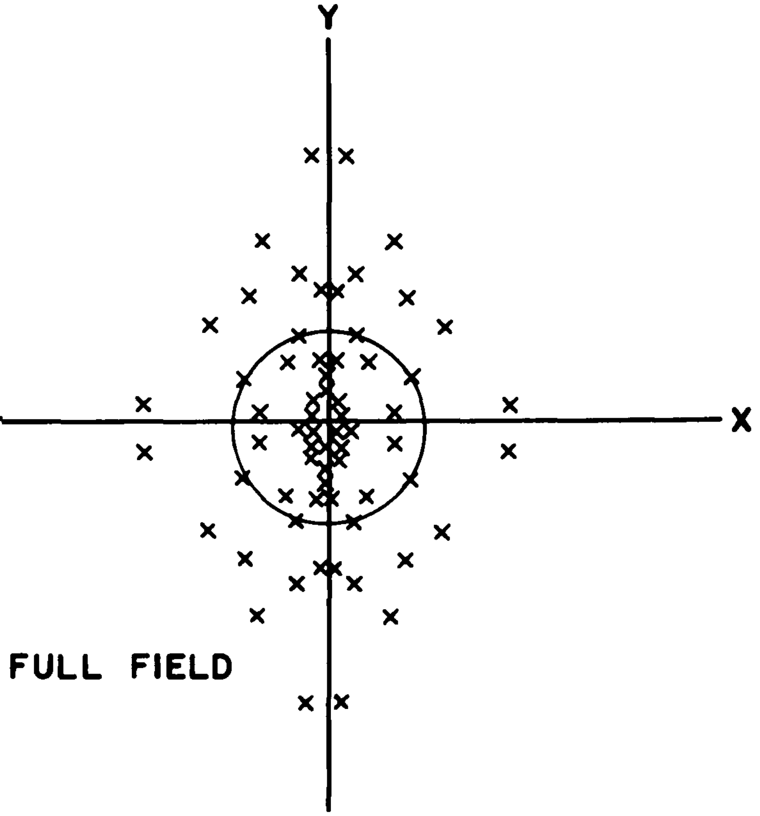
0.5 FIELD

FIGURE 11



.707 FIELD

FIGURE 12



FULL FIELD

FIGURE 13

slightly by focusing on axis and sacrificing the edges of the field.

C. Housing

The cemented doublets are contained in a housing as shown in Figure 14. The mounting brackets for attaching the housing to the guidance actuators are not shown. The field lens is mounted in a separate housing (not guided) approximately 157mm in front of the relay lens.

IV. PERFORMANCE

The relay system was manufactured by the Herron Optical Company and has been tested and installed in the IDCADS. The system meets all of the performance specifications of Section I-B. The relay lens (Figure 14) is 28mm in diameter by 44.5mm in length and weighs 115 grams.

As intended in the design approach in order to obtain the necessary field flatness, the lens has considerable negative spherical aberration. However, the required resolution (0.5 arc-seconds) is met over the entire 25.4mm field without changing the focus if the system is adjusted for sharpest focus at a point approximately 9mm from the center of the field. No refocusing is required for a spectral range from 4000A to 1μm; slight refocusing is required for sharp focus when operating in the region from 3700A to 4000A.

APPENDIX

The following specifications are for lens elements 01081, 01082, and 01084.

1. Radius accuracy: all radii shall be accurate to 5 rings.
2. Regularity: all surfaces shall be regular to 1 fringe (half wave).
3. Scratch: no scratches in excess of .01mm width. Cumulative length of scratches between .005mm and .01mm shall be less than

FIGURE 14

RELAY LENS ASSEMBLY--

1. Dimensions are in mm
2. Housing Material: 6061-T6 Aluminum
3. Finish Aluminum Parts: Black Anodize per MIL A-8625 Type 2
4. The 6.96mm Spacer may be modified during final testing

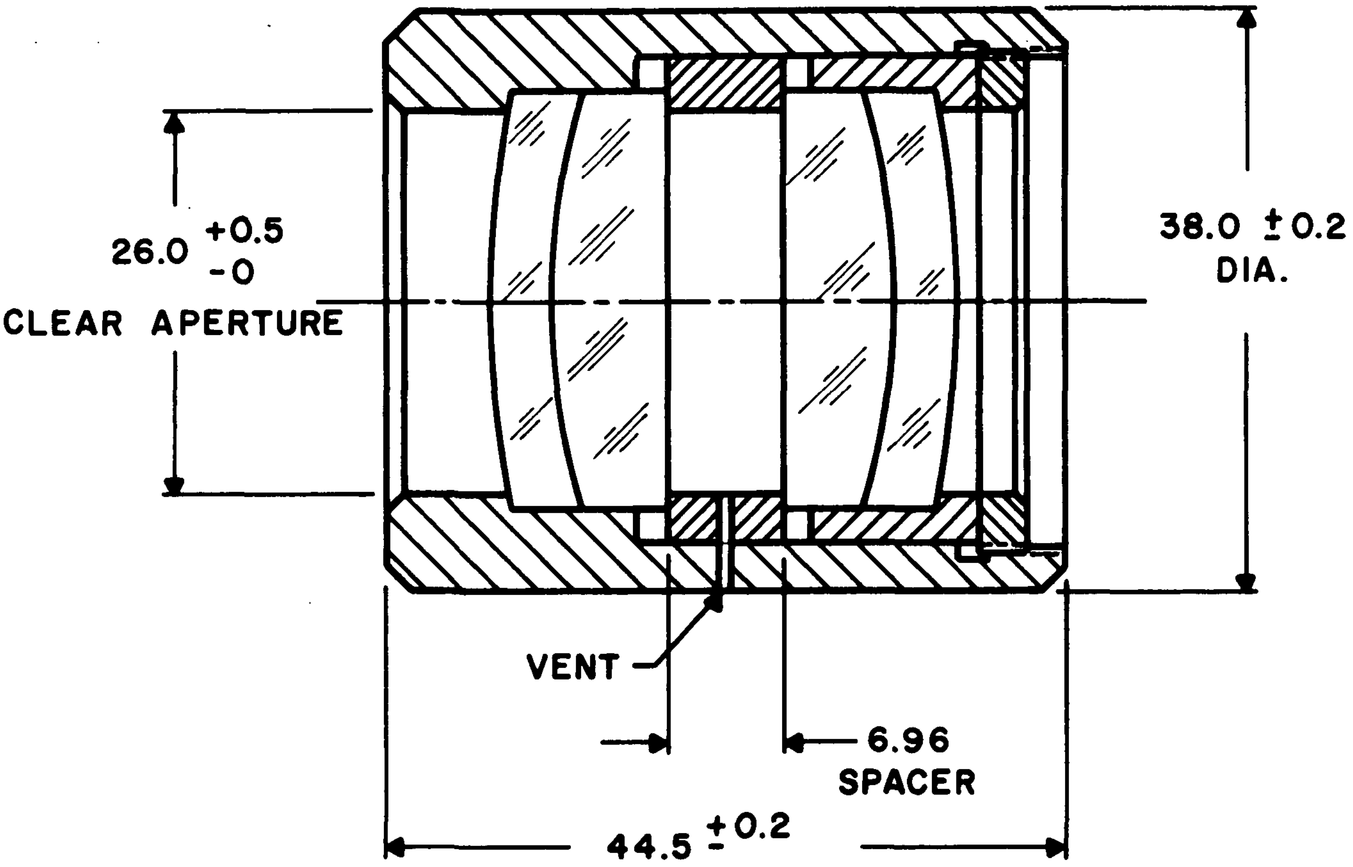


FIGURE 14

50mm. Finer scratches may be tolerated to the extent they do not constitute an unpolished condition.

4. Bubbles and digs: no digs or bubbles greater than .06mm. No more than two per element between .03 and .06mm. Finer digs and bubbles acceptable so long as they do not constitute an unpolished condition.
5. Stain: blue stains or heavy brown stains are cause for rejection. Medium brown stain is acceptable.
6. Chips and blisters: acceptable so long as they fall outside of the clear apertures.
7. Glass elements to have ordinary kiln annealing. Strain: retardation less than 10 millimicrons per cm.
8. Coating: all glass surfaces to be coated UV HEA registered or equivalent.